lower pressure at sea. The contracting channel acting like a Venturi tube increases the speed of the flow until by the time the gap at the point of ejection is reached extraordinary velocities are attained.

Winds similar in type if not in strength are to be found wherever the character of the terrain restricts to some gap or gorge the passage of air from regions of higher to regions of lower pressure. They are a common orographic phenomenon of the moving air. For this reason some special term to define and describe them seems to be demanded. Maj. E. H. Bowie has suggested the name "bottleneck winds." "Funnel winds" was used some years ago by Mr. S. L. Trotter in a paper dealing with marked incongruities in gale velocities at certain observation points on the Atlantic coast.[1] The writer has already employed the term "orographic" in referring to such winds, although in the opinion of some it is open to objection as being too general. "Gap winds" is sufficiently specific and is favored by at least one meteorologist of eminence.[2] "Orographic" would, it is true, apply to a wider variety of winds than any of the other terms suggested. It would describe winds which increase in velocity by passing *over* a mountain barrier equally as well as those which increase in velocity by passing *through* a gap or gorge. Both phenomena deserve appropriate nomenclature. They are so characteristic of the moving air as to have become a commonplace of airway weather observations in mountain districts. They occur in such regions with a consistency which would be surprising if the cause were less obvious. Orographic winds, whether of the gorge, gap, or ridge variety, are obeying in principle if not in detail the law exhibited in the functioning of a wind tunnel or a Venturi tube. In the gorge, three sides of a Venturi are roughly represented; in the ridge but one. But the constriction affecting the flow operates effectively, though in varying degree, in all cases. Indeed the term "Venturi winds" may be offered without doing violence to logic.

[1] Local Peculiarities of Wind Velocity and Movement Atlantic Seaboard—Eastport, Me., to Jacksonville, Fla., by Spencer Lee Trotter. Page 634, vol. 48, Monthly Weather Review.

[2] In a marginal comment on the author's manuscript, Prof. W. J. Humphreys wrote: "Orographic winds is not good—it is too general. Why not 'Gap winds?' That is what they are. I have a vague impression that this term has been used."

SOME EFFECTS OF CALIFORNIA MOUNTAIN BARRIERS ON UPPER AIR WINDS AND SEA-LEVEL ISOBARS

By Delbert M. Little

[Weather Bureau Airport Station, Okland, Calif., August 17, 1931]

The intensive weather service for airways, with its numerous hourly and three-hourly reports and six-hourly upper-air data, has provided an opportunity for meteorologists to examine in great detail the day to day meteorological situations. Accurate barometer readings and upper-air wind data are most important to a proper understanding of the situations portrayed by synoptic charts. Mountain barriers play an important though invisible part on the weather charts, and it therefore seems proper that some effects of these barriers on barometric pressure and winds, as deduced from the California 3-hourly airways weather charts, be presented.

Upper-air wind data for California are obtained from the following 11 pilot balloon stations, each in or near the State: Redding, Oakland, Fresno, Lebec, Los Angeles, San Diego, March Field (Riverside), Santa Maria, Reno, Nev., Yuma, Ariz., and Medford, Oreg. Of these, 7 are Weather Bureau stations, 2 Signal Corps stations, 1 a Navy station, and 1 privately maintained but cooperating with the Weather Bureau.

Of the California 3-hourly reporting stations, 15 use the mercurial barometer and are located in or just beyond the State at the following places: Eureka, Redding, Oakland, San Jose, Fresno, Bakersfield, Lebec, Estero, Los Angeles, San Diego, March Field (Riverside), Tonopah, Nev., Reno, Nev., Phoenix, Ariz., and Medford, Oreg. Reports also are received from a number of stations to the east and north of the last four named. In addition, there are 30 stations in California reporting pressure from aneroid barometers. Readings from aneroid barometers at first were of little value, (*a*) because of their uncertain height above sea level and (*b*) because of slowly changing instrumental errors. Eventually a plan was worked out to establish arbitrary corrections, to be revised from time to time, for reduction to sea level of all readings from aneroid barometers at low-elevation stations, i. e., stations less than 400 feet above sea level. Each arbitrary correction was based upon the departure of the aneroid reading from an interpolated value secured from the regular 8 a. m. and 8 p. m. seventy-fifth meridian time charts at times when "flat" pressure maps are evident and *no strong upper air winds prevailed.*

For each aneroid barometer at a high elevation a reduction table was secured from a Weather Bureau station whose elevation was approximately the same as the aneroid to be reduced. Then a small arbitrary correction was determined by the method of interpolation described above in order to fit the aneroid reading very closely to the reduction table. Arbitrary corrections are changed by a new interpolated value from time to time, thus very nearly eliminating any error due to seasonal march of temperature or changed instrumental error. It is safe to say that ordinarily the accuracy of these aneroid reductions is to within 0.03 inch of the true sea-level pressure values. With one-third of the barometers of the mercurial type well distributed over the State, it is not at all difficult to detect errors in and adjust readings of the aneroids at other stations in the network.

Approximately 50 airway and off-airway reports are entered every three hours on a base map printed from a plate of the Stanford relief model of California. The valleys and mountain ranges stand out in striking contrast to aid the meteorologist in determining the effect of the terrain on weather, as well as to visually aid pilots seeking advice as to the weather over the airway. Some of the salient facts noted on the synoptic maps are as follows:

1. Exceptionally steep pressure gradients at times prevail over mountain barriers and the isobars very frequently follow the mountains in a general way, but not exactly parallel to elevation contours.
2. In cases of extreme pressure gradients, the upper air winds immediately over the barriers are of strong to hurricane force and at nearly *right angles* to the sea-level isobars along the mountains.
3. The surface barometric pressure is increased on the windward side and decreased on the leeward side of mountain barriers in comparison with pressures reported at considerable distances from the mountains.

(To face p. 377)

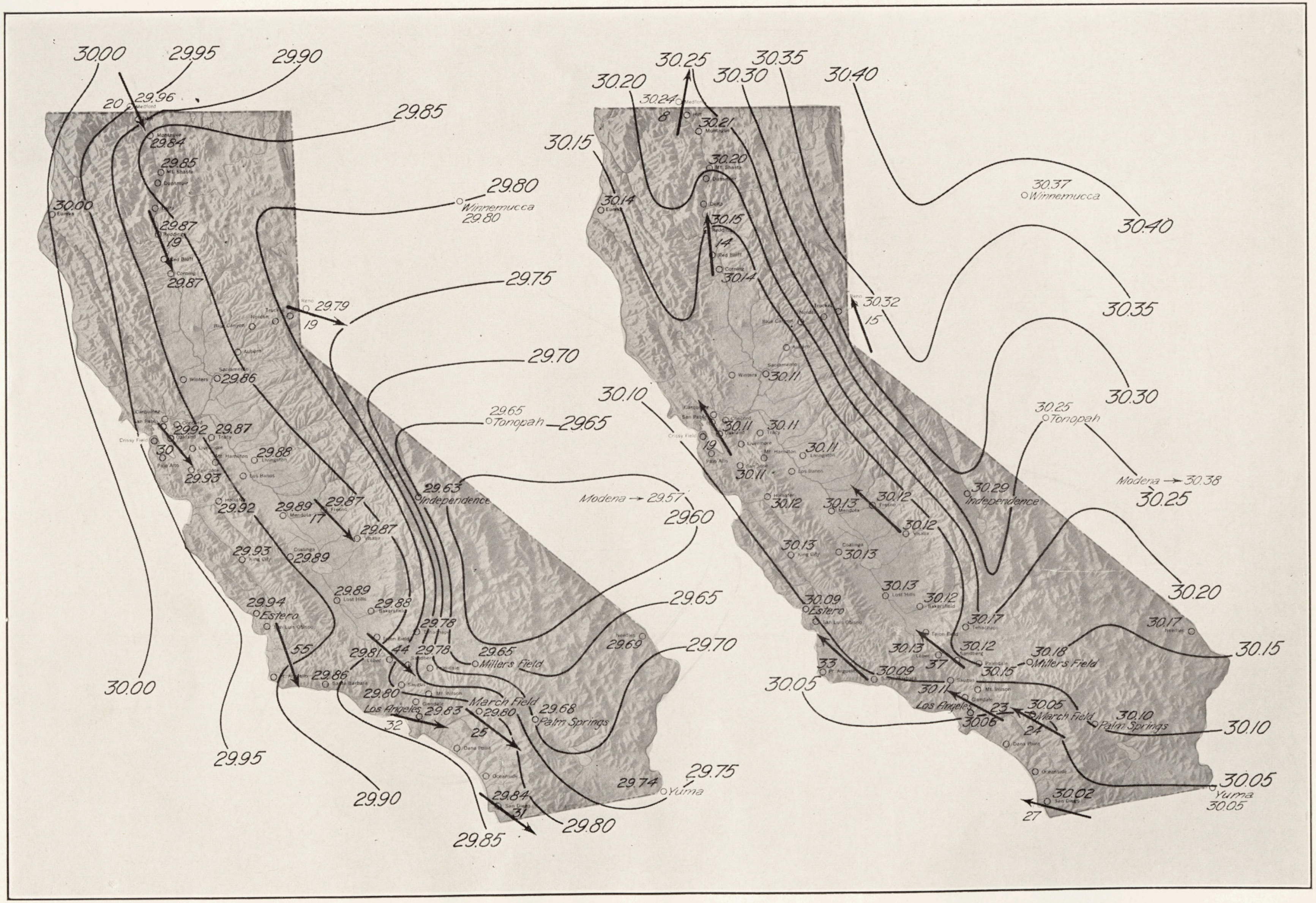

FIGURE 1.—Composite sea-level pressure maps for nine cases of extreme low pressure at Independence, Calif., in relation to Fresno, Calif., and nine cases of extreme high pressure at Independence, Calif., in relation to Fresno, Calif., during the period November, 1930, to March, 1931, with average upper air winds at 6,500 feet to 8,000 feet above sea level

4. A trough of low pressure forms rapidly in the lee of a mountain barrier as upper air winds increase in velocity in crossing the barrier.

5. The trough of low pressure on the leeward side of the mountain barrier persists for many hours after the center of the depression has passed away from the vicinity of the barrier.

Some of the best examples of extreme pressure gradients over mountain barriers in the United States are found in the Rocky Mountain States. Extreme differences in the temperatures of the air masses on the opposite sides of these mountain barriers often largely account for the differences in the computed sea-level air pressures. However, there are many cases where differences in the temperatures of the two air masses do not wholly account for the extreme pressure gradients over the mountain barriers. This was particularly noted on the California airways weather charts when, during the late fall and winter seasons, temperature differences on the slopes of the Sierra Nevada and Tehachapi ranges often were small.

Many meteorologists are familiar with the occasional large differences in the reduced (to sea-level) barometric pressures between Fresno to the west of the Sierra Nevada and Independence to the east. Some have been inclined to disregard the Independence barometer reading on the assumption that it was in error, or was faulty due to abnormal temperature. The writer studied the Independence barograph traces from November, 1930, to April, 1931, and checked them against the observed mercurial barometer readings and the reductions to sea level. Many unimportant differences in the mean temperature argument between Independence and Fresno were noted. It was found that personal errors do not enter into the reduced (to sea-level) barometric data for Independence and that the data are quite as accurate as those received from any other Plateau station, yet they appear to be more erratic. The elevation of Independence is 3,957 feet, which is somewhat lower than the average Plateau station.

Nine cases of extreme low pressure and nine cases of extreme high pressure at Independence in relation to Fresno were selected from the charts of November, 1930, to March, 1931, inclusive. Composite pressure maps for the nine cases of each type of pressure distribution were prepared as shown on Figure 1. All of the aneroid and mercurial sea-level barometric data received from the airways reports were used. Isobars were drawn for each 0.05 inch of pressure to bring out the pressure gradients over California in more detail. From inspection of the upper air winds shown on the maps for the several days selected, it was evident that northwest and west-northwest winds were associated with relatively low pressure at Independence, and southeast or east-southeast winds with relatively high pressure. The average velocity and direction of the winds at 6,500 to 8,000 feet above sea level were plotted on each map in Figure 1.

In order to determine whether there was a relation between the velocity of the upper air winds and the pressure gradient between Independence and Fresno, the upper air wind data at Lebec (elevation above sea level, 3,576 feet) were selected as being most typical. The upper air winds for Fresno were not used because of the topographic or shielding effect of the Sierra Nevada. East to southeast winds were selected because of the absence of stormy weather during their prevalence and consequent completeness of the upper air data. Resultant velocities were computed for each minute of observation for 45 balloon runs with east to southeast winds of moderate to gale velocities at Lebec during November, 1930, to March, 1931. The graph of these resultant velocities at Lebec indicates that the winds reached the highest velocities at altitudes ranging between 5,700 and 7,400 feet above sea level, and attained from the fourth to sixth minutes of the balloon run. The individual data for these altitudes, then, should be the most significant in determining whether a relation exists between east to southeast wind velocities over the mountain barrier and the high pressure at Independence. Ninety-five cases during the period referred to were used in which the Independence sea-level pressure was higher than that at Fresno and the upper air winds from the fourth to the sixth minute observation at Lebec were from the east to southeast. Using these selected data, the table of averages shows that with increasing velocity of the wind the pressure becomes higher at Independence than at Fresno.

Average velocities in miles per hour of east and southeast winds for the fourth to sixth minutes of balloon runs at Lebec, Calif., during November 1930, to March 1931

Sea-level barometer at Independence higher than at Fresno by—	Difference in mean temperature argument Independence and Fresno	
	84 cases of 0° to 13° F.	11 cases of over 13° F.
	Miles per hour	*Miles per hour*
0.04 to 0.06 inch	14	13
0.07 to 0.11 inch	23	15
0.12 to 0.17 inch	27	22
Over 0.17 inch	35	20

We are not in the habit of thinking that winds cause a pressure gradient but rather that a pressure gradient causes winds. However, when an air mass is flowing over a mountain barrier, undoubtedly there is a tendancy toward compression on the windward side and an expansion on the leeward side of the mountain. An abnormal pressure gradient in the vicinity of the barrier results. It might be argued that the air is free to rise vertically and a compression could not exist, but there is undoubtedly a restraining force due to the increased momentum of successive layers of air involved. It might also be argued that the data in the table could be transposed to prove that the winds are gradient winds caused solely by the pressure gradient. If this is the case, then it is not apparent how the belt of slightly excessive pressure along the east side of the Sierra Nevada is maintained for several days at a time, except by the explanation of wind action against the mountain barrier, i. e., compression. (See the map at the right in fig. 1.)

A similar phenomenon occurs along the shore line of California, Oregon, and Washington when on-shore winds prevail.[1] It is at times particularly marked because there is no coastal plain, and fairly steep mountain ranges parallel the shore line from southern California to the Canadian border. As long as the winds in the lower layers of the atmosphere are southeasterly the phenomenon is not apparent on our maps, the "refrac-

[1] Sir Napier Shaw, Manual of Meterology, Vol. IV (Part IV) pages 98–99.

There is moreover another reason why a station on the coast presents a complication in the relation of observed wind to gradient which may be operative in windy weather when the local gradient of temperature is not very markod. This second reason is the dynamical effect upon the stream of air due to the sudden transition between a surface with a comparatively low coefficient of eddy viscosity, such as the sea, and one with a comparatively high coefficient, such as a land surface, particularly a hilly or rugged land surface. This change must probably be represented by a sudden transition of pressure in the surface layers which produces a "refraction" of the isobaric lines on crossing the coast. * * * The mere addition of the volume of the land to that of the air which passes over it must produce some increase of the pressure at sea level.

tion" probably being slightly reversed with winds off shore at an acute angle, but as soon as a cyclone in the north approaches the Canadian coast and the winds veer, the phenomenon appears on our airways maps and becomes more marked as the winds veer to westsouthwesterly. This "refraction" of the isobaric lines therefore gives us immediately knowledge that the winds are veering during periods of stormy weather with the cyclone to the north and usually with upper air data missing. This is a distinct aid in forecasting airway weather conditions for short periods in advance.

Compression effect on the windward side of a mountain barrier does not fully explain its counterpart, namely the barometric troughs on the leeward side. In order to have a better understanding of the entire phenomenon, it would be of advantage to know, in a general way, how air flows over a mountain barrier. With single theodolite balloon runs, it is not possible to determine, from the individual runs at Lebec, the amount of vertical component in the lower levels and whether at some average

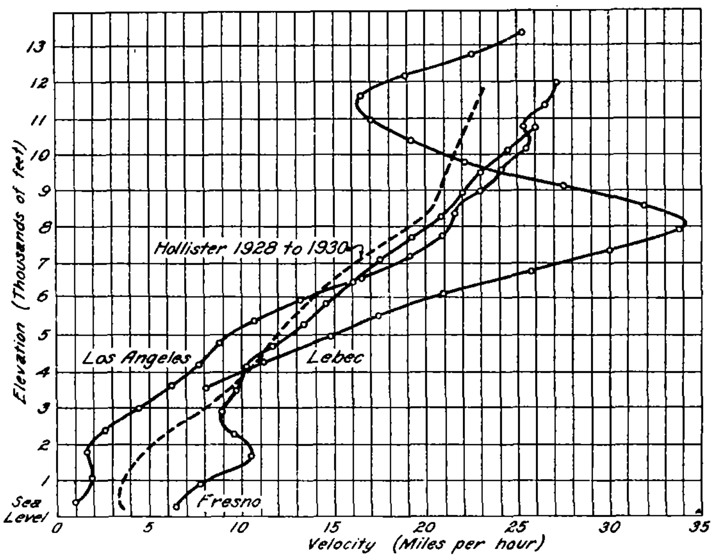

FIGURE 2.—Resultant velocities of north northwest and northwest winds over Fresno, Lebec, and Los Angeles, Calif., during the period November, 1930, to March, 1931, inclusive. Resultants computed from 71 to 85 runs nearly simultaneously, at the three stations with data nearly complete to the highest altitudes

altitude there ceases to be a vertical component to the winds over the mountain barrier. However, some interesting evidence bearing on this question has been obtained by comparison of graphs of resultant velocities for west-northwest to north-northwest winds at Lebec and surrounding pilot-balloon stations.

Graphs of resultant velocities over Fresno, Lebec, and Los Angeles for all cases of west-northwest to north-northwest winds over central and southern California during November, 1930, to March, 1931, inclusive, were prepared (see figure 2), from data which were nearly complete to 12,000 feet above sea level. The resultant directions were, of course, northwest to north-northwest or nearly parallel to a line running through Fresno, Lebec, and Los Angeles. The graph for Lebec shows extreme velocities at about 8,000 feet above sea level. A decided change in slope of the curve for Los Angeles at about 8,000 feet above sea level, and a faint bulge in the curve for Fresno at about the same elevation stand out prominently. A similar resultant velocity graph for Santa Maria with less data available shows a decided change in the slope of the curve at slightly above 8,000 feet. Data from short balloon runs were discarded in computing these resultants and the data are 90 per cent complete at the highest levels.

To prove that the changes in the slopes of curves at 8,000 feet were not peculiar to the period selected, 188 cases of north to west-northwest winds over Hollister, Calif., from October, 1928, to September, 1930, were used and the resultants computed. The data were 95 per cent complete to the highest level, all short runs being discarded. A decided change in slope of the curve for Hollister at 8,000 feet above sea level is shown. From these graphs it appears that practically all topographical retardation in velocity of northwest winds over the Tehachapi and coastal ranges of mountains has been eliminated at 8,000 feet above sea level.

It is important to note that only two or three peaks in these ranges of mountains extend to 8,000 feet.

It should not be assumed that most of the air when moving southeastward over the San Joaquin Valley below the mountain barriers, is forced upward and crosses the Tehachapi Mountains. This is not the case, for the balloon runs for Fresno show that on numerous occasions a large anticlockwise eddy, with vertical axis, at elevations averaging between 2,000 and 5,000 feet above sea level, while winds near the surface and above these altitudes are moderate to strong north to northwesterly. This great valley eddy is not always marked by winds of opposite direction at those levels over Fresno, but its effect on often noted in the marked decrease in velocity of north to northwest winds at those levels. This is important from an aircraft pilot's standpoint as he may often escape the full effect of northwest head winds by flying at about 3,000 feet along the eastern side of the San Joaquin Valley.

The resultant velocities of northwesterly winds at elevations between 6,500 and 11,000 feet above sea level over Fresno are approximately equal to the resultant velocities at corresponding elevations over Los Angeles. The resultant velocities for similar winds over Lebec, in the Tehachapi Mountains, do not show this similarity because of the extreme velocities at 8,000 feet above sea level. A somewhat striking chart of the extreme velocities of the northwest winds is obtained by plotting a series of individual balloon runs on a single graph. (See fig. 3.) The extreme velocities of air flowing over a mountain barrier may be explained by assuming that the velocity increases as a considerable portion of the air passes through a restricted outlet. Part of the abnormal velocities observed at this level may be fictitious and due to insufficient rise of the balloon on entering the rapidly-moving air stream, but if there is any upward vertical component to the air, which seems possible because Lebec is on the north slope of the range, the error would be minimized.

Similar graphs of the resultant velocities of southwesterly winds over Fresno and Reno (see fig. 4) show the maximum velocities over the Sierra Nevada, as indicated by the Reno graph, at about 11,500 feet above sea level. The average height of the Sierra Nevada west of Reno is approximately 3,000 feet greater than the average height of the Tehachapi. This accounts for the greater height above sea level of the extreme velocities observed over the mountain barrier at Reno than over that at Lebec.

The increased velocity of the free air, immediately over mountain barriers, then, no doubt causes decreased pressure on the leeward side of the barriers. This phenomenon may be said to be similar to the decreased pressure on the upper surface of an airfoil in flight,[3] the mountain

[3] For an excellent explanation of this phenomenon see "A Philosophy of Lift" by H. F. Lusk, MS. published in United States Air Services, March, 1931.

range being roughly similar to the upper surface of an airfoil.

To illustrate the phenomenon described, a map is presented (see fig. 5), on which all of the data from the airways weather reports are used. Isobars are drawn for

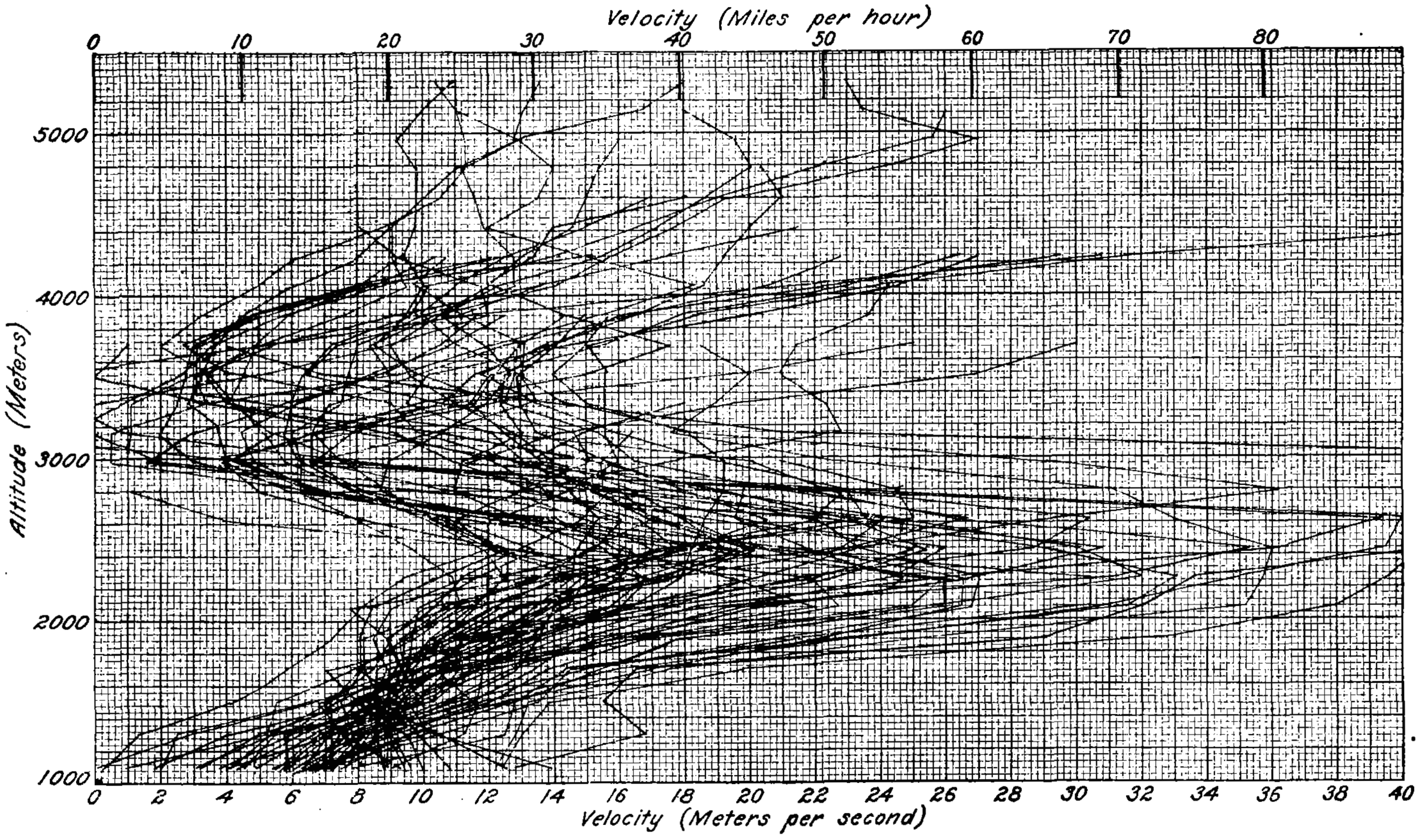

FIGURE 3.—Extreme velocities of northwest winds up to 6,000 meters above Lebec, Calif., from November, 1930, to March, 1931

each 0.05 inch of pressure to bring out the gradients. The map is of an unusual storm in which northeasterly gales prevailed over Washington, Idaho, northern Nevada, and northern California on the afternoon of April 22, 1931.[3] The barometer reading reduced to sea level at Blue Canyon on the west or leeward side of the Sierra Nevada, was 29.17 inches at 2 p. m., while the reading at Sacramento was 29.36, and at Reno 29.48. When the Blue Canyon barometer was falling steadily, the writer sent five messages over the airways teletype system to verify the accuracy of readings. Later he personally talked to the observer and examined the original record of hourly observations. All readings made during the day are considered accurate. No instrumental error, or error in method of reduction to sea level, is apparent, as the reduced readings, for Blue Canyon a day or more later returned slowly to their normal values, as shown by the mercurial barometer readings for Sacramento and Reno, but only after the northeasterly upper air winds ceased. The area of low barometer on the leeward side of the mountain barrier was caused, no doubt, by the effect of northeast gales on crossing the Sierra Nevada.

Dust and sandstorms from northeasterly gales were very bad in Washington, Oregon, and northern California on that afternoon, and the following day the S. S. *Maui* reported a heavy dust storm at sea approximately 500 miles west-southwest of the Golden Gate. This rather extraneous statement will assist the reader in identifying the day on which this meteorological situation prevailed.

[3] cf. Cameron, Donald C., great dust storm in Washington and Oregon April 21–24, 931. This Review 59:195–97.

There is still another interesting phenomenon observed in many of the Lebec runs which is indicated on the Lebec northwest wind resultant curve when it is compared with those of Fresno and Los Angeles. It should be kept in mind that the balloon runs used to compute the three resultant graphs were selected from as nearly simultaneous observations as possible. It will be noted that the resultant velocity at 11,000 feet above sea level at Lebec

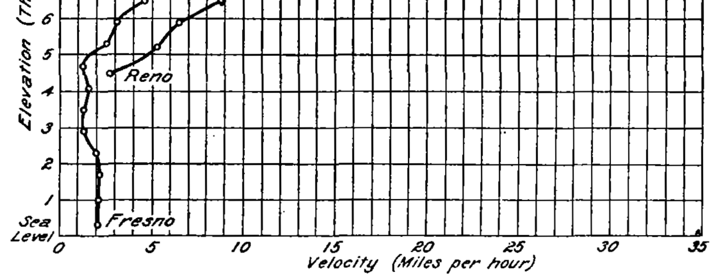

FIGURE 4.—Resultant velocities of west and southwest winds over Reno, Nev., and Fresno, Calif., during the period November, 1930, to April, 1930, inclusive. Resultants computed from 45 runs at Reno and 36 at Fresno most of which were made approximately simultaneously and the data are nearly complete to high levels

s approximately one-third less than at the same elevation ov e r Fresno and Los Angeles. In several individual cases when the winds over Lebec were northwesterly, a light

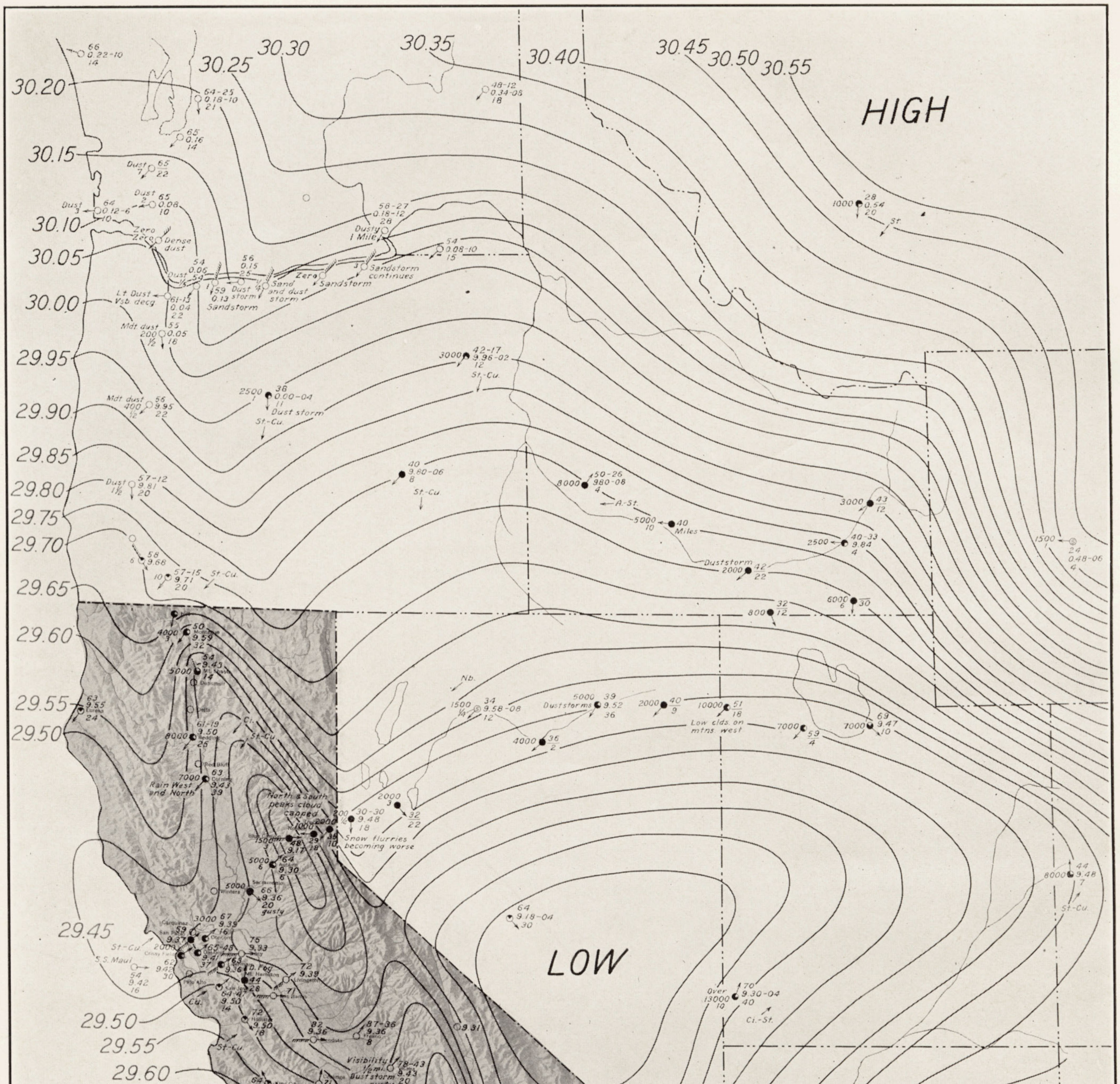

FIGURE 5.—Weather map 2 p. m. (P. S. T.) April 22, 1931. See also this REVIEW May, 1931, pp. 195–197

southeasterly wind has been noted at 11,000 feet above sea level with northwesterly gales below and aloft. An explanation of this phenomenon is offered herewith. The extreme velocity at 8,000 feet represents an increase in kinetic energy with a corresponding decrease in pressure energy according to the Law of Conservation of Energy.[4] The extreme velocity or kinetic energy is reduced after passing over the mountain range with a corresponding increase in pressure energy which acts similarly to a pressure head in a body of water when a rapidly moving stream enters it. There is a return flow on each side of the fast-moving stream, but in the case of the air moving rapidly over a mountain barrier the return flow is manifest only above and below the rapidly moving air stream. The return flow near the surface on the leeward side of a mountain barrier has often been noted. The return flow aloft is superimposed upon the velocity of the air mass moving over the mountain barrier which corresponds to a marked decrease in velocity. In the case of Lebec, the phenomenon has its maximum effect at 11,000 feet above sea level.

The phenomenon of increased pressure on the windward side and decreased pressure on the leeward side of mountain barriers should be kept in mind during the preparation of weather charts. It will often solve the question of apparent discrepancies in barometer readings and it is an important clue to direction and velocity of upper air winds when the latter data are missing on synoptic charts.

[4] For the mathematics of this phenomenon see page 206, second edition, Physics of the Air, by W. J. Humphreys.

DESERT WINDS IN SOUTHERN CALIFORNIA

By FLOYD D. YOUNG

[Weather Bureau office, Pomona, Calif., July 20, 1931]

The southern California coastal plain, one of the richest agricultural sections in the world, depends to a great extent on the mountain barriers on the immediate north and east for its comparative freedom from continental climatic influences. The mountains are effective for the most part in shutting out the desert climatic extremes, but there are times when they fail to afford complete protection.

Whenever a strong area of high barometric pressure moves in or develops over the Plateau region, the barometric gradient calls for northeast or east winds in southern California. Winds from either of these directions bring air from the elevated land areas of Nevada and nothern Arizona. The descent of this air to sea level along the southern California coast causes a warming by compression in the neighborhood of 27° F. When we consider that these desert air masses usually are relatively dry before this mechanical warming takes place, it is easy to account for the extremely low humidities sometimes registered during the progress of a desert wind in southern California.

Desert winds may occur in southern California almost any month in the year, but those which come during the summer months are usually light, and of minor importance from the standpoint of damage to crops. They do, however, cause exceptionally high temperatures and low humidity, with consequent acute fire hazard.

The most destructive desert winds occur during the fall and winter months, when temperatures are likely to be close to zero in Nevada. During the progress of these winter winds, temperatures usually are not unseasonably high in southern California, but the relative humidity is sometimes extremely low. Readings of the sling psychrometer at Pomona, made with the utmost care, have indicated relative humidities of 3 per cent. Psychrometer readings at such low humidities are, of course, subject to error, but it is probable that the relative humidity falls about as low in this region as anywhere in the world.

The air moving outward from the Plateau high-pressure area is blocked on the south by the San Gabriel and San Bernardino Mountains. Wherever there is a break in these southern chains, such as Cajon Pass, the desert air streams through it and out onto the Great Valley of southern California. If the pressure difference between Neavada and southern California is only moderate (0.16 to 0.40 inch) the desert winds usually are confined to rather narrow belts extending from the mouths of the passes to the ocean by the lowest and least obstructed routes. The air stream which issues from Cajon Pass under these circumstances probably is of greater interest and importance than any of the others.

Cajon Pass lies between the San Gabriel and San Bernardino Mountain ranges, extending roughly north and south, turning toward the southeast near its southern extremity. It is a V-shaped notch about 17 miles long and quite narrow, extending from the Mojave Desert on the north to the Great Valley of southern California on the south. The slope from the summit of the pass northeastward to the Mojave Desert is gradual, the summit being only slightly higher than the general level of the desert. The fall from the summit toward the south is more abrupt, averaging about 115 feet to the mile. The approach to the pass from the desert side is shaped like a great horizontal "V," with the sides formed by the mountains, which converge at the entrance.

Desert winds are seldom felt on the floor of the pass, but appear to remain at some elevation above the ground. Looking down from the San Bernardino Mountains during the progress of a moderate wind, the first clouds of dust appear about a half mile south of the southern gate.

These air streams from Cajon Pass usually maintain their identity in a remarkable manner. They move out over the valley floor (almost level to the eye, but actually sloping towards the south and west), swing toward the southwest, and either follow the canyon of the Santa Ana River through the Santa Ana Mountains or move directly over the low mountains south of the canyon and then follow a well-defined path over the almost level plains of Orange County and reach the ocean in the vicinity of Newport. On going eastward in the open country some 7 miles south of Cajon Pass, with light to gentle variable winds, one often passes abruptly into an air stream moving from the north-northeast at a velocity of 30 to 35 miles per hour. The easterly limits of the stream usually are just as well marked, and one passes from a near gale into a region of relative calm within the space of half a mile. The width of the air stream under these conditions probably will average about 5 miles. The same air current often is encountered in the perfectly open plains 15 miles or so to the southwestward, with its velocity and width substantially unchanged, and relatively calm air on either side. The stream may shift its position slightly from time to time, but appears to change but little in width or velocity. Sometimes it